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First-generation Low-energy Buildings: Quality of the Thermal Envelope

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Keywords: thermal envelope, quality, low-energy, building, evaluation, thermographic observations, on location

ABSTRACT

This paper focuses on the thermal envelope of buildings. The energy consumption of buildings is estimated to nearly 50% of the Danish energy production. Energy is used for hot water, heating and comfort and plays a very important role in the endeavour to reduce CO₂ emissions. Introducing low energy buildings, it is important that the heat loss through the thermal envelope is reduced both in design and in practice when constructing the building. Therefore it is important to assess whether the quality of the construction of the thermal envelope comply with specifications outlined in the design descriptions of these buildings.

The thermal envelope of nine first-generation low-energy buildings constructed as individual dwellings built in Denmark between 2006 and 2008 was visually observed by means of thermographic equipment. Measurements revealed the quality of the thermal envelope. The paper evaluates the selected construction solutions carried out both to achieve a high-performance thermal envelope and to prevent thermal bridges. Thermographic observations of the thermal envelope of buildings constructed before 2006 were used to evaluate the quality of high-performance thermal envelopes. The paper shows that improvements are needed both at the design of high-performance thermal envelopes as well as during implementation.

1. Introduction

The energy consumption of buildings play an important role in the discussion of climate change, CO₂ emissions and strategies for intelligent energy use and distribution. In 2005, the Danish Government presented an action plan aiming to promote significant results in the energy field. This action plan sets goals for the Danish energy sector for the years leading up to 2025. Moreover, it outlines what long-term efforts must be made in order to keep energy consumption at current levels in the run-up to 2025. As a consequence, energy provisions in the Danish Building Requirements were changed in 2006 from individual requirements for the average coefficient of heat transmission of building components to requirements covering the total energy consumption of buildings. At the same time, the energy requirements were tightened in order to achieve an energy reduction of 25% for new buildings. Further tightening introduced in 2010 was estimated to result in an additional energy reduction of 25%. The tightened energy provisions paved the way for further tightening in 2015 and 2020. Each tightening is expected to result in a 25% energy reduction. The action plan is to meet the obligations outlined in the Kyoto Protocol which limits emissions of greenhouse gases in the period 2008 to 2012 for signatory industrialised countries.

The effort of preparing a new climate policy agreement failed at the Conference of the Parties (COP) meetings number 15 (COP15) and 16 (COP16), held in Copenhagen and Mexico City in December 2009 and 2010, respectively. This was intended to succeed the Kyoto Protocol (UNITED NATIONS 1998) by introducing obligations to limit emissions of greenhouse gases after 2012. Prior to the COP15 meeting in 2009, the heads of state and the heads of government of the European Union countries agreed on the vision of the Presidency Conclusions at the European Council on 29 and 30 October 2009 at Brussels (COUNCIL OF THE EUROPEAN UNION 2009). The ambition was to

limit global warming to a maximum of 2°C and that industrial countries should in total reduce their emissions of greenhouse gases by 80-95% in 2050 compared with 1990 emissions. As a consequence, the Danish Commission on Climate Change Policy presented their ambitions in 2010. These ambitions outline Danish energy-saving initiatives, energy supply investments, energy distribution and ways to mitigate the effects of climate change in the years leading up to 2050.

Buildings comply with the energy provisions by decreasing the average coefficient of heat transmission, the U-value, and by reducing the air leakage of the thermal envelope combined with technical solutions for heat recovery and energy supply. However, it is important for the effort to reduce the energy consumption of buildings to establish whether the quality of the construction of the thermal envelope complies with specifications to the heat transmission outlined in the drawings in the design phase of the building.

The thermal envelope of nine first-generation low-energy buildings constructed as individual dwellings built in Denmark between 2006 and 2008 was visually observed by means of thermographic equipment. Measurements showed the quality of the work carried out on location. During winter the exterior walls were observed by means of commercially available thermographic equipment. The performance was assessed on the basis of these on-location studies. The investigation covered a real-life situation where the inhabitants and normal weather conditions influenced the thermal insulation. For further details see (Kristensen, L. et al. 2010). The paper sets targets for improvements needed to comply with the requirements for high-performance thermal envelopes.

2. Thermal performance

The thermal performance of high-performance exterior walls was investigated to uncover any failures in the thermal performance i.e. thermal bridges, cavities without thermal

insulation and incorrect insulation work. The investigation was carried out using commercially available thermographic equipment.

All the investigated dwellings passed the air permeability test measured by using the method described in DS/EN 13829 and ISO 9972:2006. One method for measuring the air permeability of a building is the Blower Door Test, which was used. The air permeability was measured to be lower than 1.5 l/s per heated occupied m² of the individual dwellings, measured as the mean of the infiltration and the exfiltration for a negative and a positive interior pressure of 50 Pa, respectively.

2.1 Meters for thermographic observations

The exterior walls were observed by means of commercially available thermographic equipment. The exterior walls were observed from the inside of the dwellings. Observations were stored as digital images on a PC and a computer program was used to view and measure the temperature at locations of interest. Image analysis was used to measure and visualise thermal bridges found in the thermal envelope. The thermographic observations were carried out in the middle of March on a day with stable weather conditions and a temperature of 6 °C, no wind to a slow breeze from southeast with a little sun during the day.

A value of reference for temperature and relative humidity was measured on location for each dwelling individually and keyed in the thermographic equipment.

The emission was set to 0.91, which is the emission for white paper as the individual dwellings had wallpaper painted white on the internal surface of the exterior wall.

2.2 Dwellings

Eight individual dwellings were investigated. The dwellings were individually owned and individually constructed by different contractors. Dwellings were constructed as low-energy buildings with focus on a high-performance thermal envelope and the prevention of thermal bridges and incorrect insulation work. Dwellings are introduced by a picture and a brief description below. Different principles for constructing different thermal envelopes are outlined.



Fig. 1. Three of the dwellings had exterior walls consisting of brickwork walls attached to a lightweight concrete wall that served as the loadbearing inner wall, separated by thermal insulation made of mineral fibre. The dwelling had a

cold attic room. The floor construction consists of a concrete slab on a layer of expanded polystyrene, EPS, insulation on top of a capillary-braking layer. The overall coefficient of heat transmission of the ground deck, roof and exterior walls was 0.1, 0.08 and 0.18 W/m²K, respectively. The concrete slab floor was separated from the strip foundation by 30 mm EPS insulation.



Fig. 2. Two of the dwellings had exterior walls consisting of brickwork walls covered with plaster attached to a wood-stud wall with mineral fibre insulation that served as the load-bearing inner wall. The wood frame wall allowed the vapour barrier to be placed 50 mm into the insulation. The internal surface was gypsum boards. The ceiling of the dwellings was parallel with the roof. The horizontal partition included timber beams. The floor construction consisted of a concrete slab on a layer of EPS insulation on top of a capillary-braking layer. The overall coefficient of heat transmission of the ground deck, roof and exterior walls was 0.11, 0.15 and 0.18 W/m²K, respectively. The concrete slab was separated from the strip foundation by 30 mm EPS insulation.



Fig. 3. One dwelling had exterior walls consisting of brickwork walls attached to a lightweight concrete wall that served as the loadbearing inner wall separated by thermal insulation made of mineral fibre. The ceilings of the dwelling were parallel with the roof. The horizontal partition was lightweight concrete. The floor construction consisted of a concrete slab floor on a layer of EPS insulation on top of a capillary-braking layer. The overall coefficient of heat transmission of the ground deck, roof and exterior walls was 0.11, 0.09 and 0.17 W/m²K, respectively. The concrete slab

floor was cast to reach the strip foundation. The strip foundation consisted of blocks of leca separated by thermal insulation.



Fig. 4. One dwelling had exterior walls of timber attached to a wood-stud wall with mineral fibre insulation that served as the loadbearing wall. The wood frame wall allowed the vapour barrier to be placed 50 mm into the insulation. The internal surface was gypsum boards. The ceiling of the dwelling was parallel with the roof. The horizontal partition included timber beams. The floor construction consisted of a concrete slab floor on a layer of EPS insulation on top of a capillary-braking layer. The overall coefficient of heat transmission of the ground deck, roof and exterior walls was 0.07, 0.12 and 0.13 W/m²K, respectively. The concrete slab was separated from the strip foundation by 30 mm EPS insulation.



Fig 5. One dwelling had exterior walls of brickwork walls attached to a wood-stud wall with mineral fibre insulation that served as the loadbearing inner wall. The internal surface was gypsum boards. The ceiling of dwelling was parallel with the roof. The floor construction consisted of a concrete slab on a layer of EPS insulation on top of a capillary-braking layer. The overall coefficient of heat transmission of the ground deck, roof and exterior walls was 0.12, 0.13 and 0.20 W/m²K, respectively. The concrete slab was cast to reach to the strip foundation. The strip foundation consisted of blocks of leca separated by thermal insulation.

3. Results

Thermographic observations revealed local areas in the thermal envelope with a lower temperature than at the overall inner surface of the thermal envelope. Temperature decrease at local areas revealed lower thermal performance at the thermal envelope locally.

The thermographic observations were divided into seven categories. The seven categories denoted A to G described the types of failure observed, as:

A: Cold joint between exterior wall and ceiling

B: Cold corner at exterior wall

C: Cold skirting board along exterior wall

D: Cold areas at rafters placed on loadbearing inner wall

E: Cold areas in the thermal envelope

F: Cold areas in the thermal envelope along sealing

G: Cold joints between building components

The surface temperature was observed by using thermographic equipment and by analysing thermographic digital pictures in colours. Temperatures were measured by means of the colour scale in each picture and by using a PC. Table 1 shows the measurements in the individual categories, A - G. A more detailed description of the observations made for the individual categories are given in sections 3.1 to 3.7

Table 1. Temperature measurements are taken from the thermographic digital pictures and divided into the seven categories described above. The temperature difference is the difference between the overall temperature of the surface and the lowest temperature observed, divided into categories. Some of the digital pictures include more than one example of the category observed. In that case, the temperature difference is measured as the highest temperature difference measured as the result of the category observed. Not all categories are represented in every dwelling observed. The average temperature decrease of each category is also shown.

Category	Temperature difference (°C)	Average temperature (°C)
A	3 - 5	3.9
B	3 - 5	4.25
C	3 - 5	4.3
D	2 - 5	3.5
E	5 - 10	7.3
F	4 - 6	4.7
G	4 - 12	6.4

3.1 Category A: Cold joint between exterior wall and ceiling

Category A covers the joint between exterior walls and the ceilings for cold attic rooms as well as for the ceiling at horizontal divisions at exterior walls. In addition, at inwards as well as outwards corners at the ceiling, balconies and corners at the entrance are included.

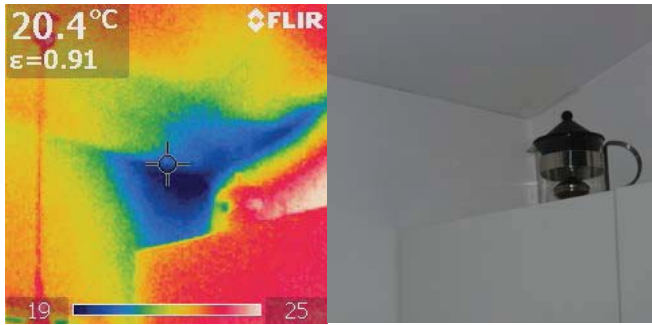


Fig. 6. The joint between the exterior wall, the party wall and the ceiling in the kitchen. The exterior walls were brickwork walls attached to a lightweight concrete wall that served as the loadbearing inner wall separated by thermal insulation made of mineral fibre. The party wall was a lightweight concrete wall. The ceiling consisted of two layers of gypsum board attached to laths with insulation material between and above the laths. The thermal insulation was made of mineral fibre placed towards the ventilated cold attic room. A PE vapour barrier was placed behind the gypsum boards. On the thermographic picture to the left, the dark blue colour represents 19 °C and the yellow colour represents 23 °C. The picture to the right is an ordinary photo.

3.2 Category B: Cold corners at exterior walls

Category B covers vertical corner between exterior walls both at inwards as well as outwards corners from floor to ceiling.

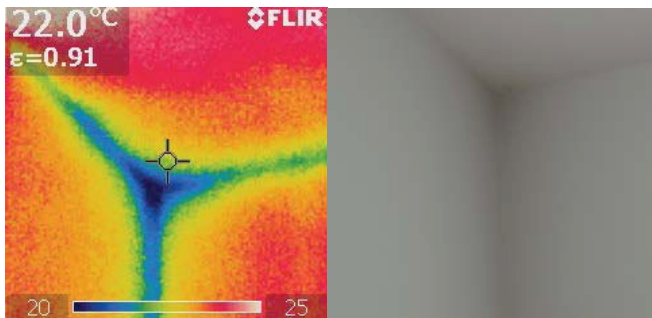


Fig. 7. The joint between two exterior walls at the ceiling in a combined living room and kitchen-dining area. The exterior wall was a brickwork wall attached to a wood-stud wall with mineral fibre insulation that served as the loadbearing inner wall. The internal surface consisted of gypsum boards. The ceilings of the dwellings were parallel with the roof. A PE vapour barrier was placed between the two layers of gypsum. Thermal insulation of mineral fibre was placed between the rafters in the roof construction. On the thermographic picture to the left, the dark blue colour represents 20 °C and the red colour represents 25 °C. The picture to the right is an ordinary photo.

3.3 Category C: Cold skirting boards along exterior walls

Category C covers cold skirting boards and was observed in a limited number of dwellings. Cold skirting boards along the exterior wall were only observed at the strip foundation at the ground floor.

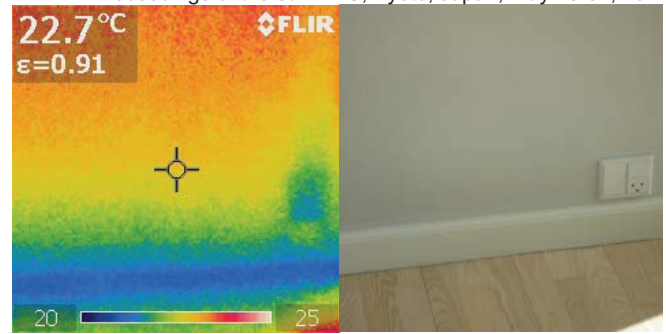


Fig. 8. The cold skirting board along the exterior wall towards the floor in the combined living room and kitchen-dining area. The exterior wall was a brickwork wall attached to a lightweight concrete wall that served as the loadbearing inner wall separated by thermal insulation of mineral fibre. The floorboards were 14 mm parquet on polyester felt. The ground deck was a 100 mm concrete slab on 275 mm coated loose light clinkers. The strip foundation consisted of two sections of two lightweight concrete blocks separated by 100 mm thermal insulation placed on top of concrete cast to reach stable ground at 0.9 m below ground level. On the thermographic picture to the left, the dark blue colour represents 20 °C and the yellow colour represents 23 °C. The picture to the right is an ordinary photo.

3.4 Category D: Cold areas at rafters placed on loadbearing inner walls

Category D covers cold joints between the exterior wall and the ceiling and was made in a limited number of dwellings. The location of rafters placed on heavy back walls and wood-stud back walls was observed by use of thermographic observations. The locations of the rafters were shown as spots at regular intervals with a lower temperature than was observed at the overall thermal envelope, the exterior wall and the ceiling.

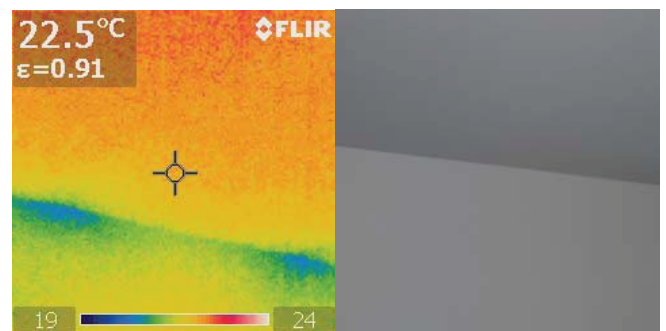


Fig. 9. Joint between the exterior wall and the ceiling in the utility room. The exterior walls were brickwork walls attached to lightweight concrete walls that served as the loadbearing inner wall separated by thermal insulation of mineral fibre. The ceiling consisted of two layers of gypsum board attached to laths with insulation material between and above the laths. The thermal insulation was made of mineral fibre placed towards the ventilated cold attic room. A PE vapour barrier was placed behind the gypsum boards. On the thermographic picture to the left, the dark blue colour represents 19 °C and the red-yellow colour represents 24 °C. The picture to the right is an ordinary photo.

3.5 Category E: Cold areas in the thermal envelope

Category E includes inhomogeneity in the thermal envelope seen both in the exterior walls and towards the ceiling. The areas represent thermal bridges or areas with a decreased thickness of the layer of the thermal insulation.



Fig. 10. Joint between the exterior wall and the ceiling. The exterior walls were a brickwork wall attached to a lightweight concrete wall that served as the load-bearing inner wall separated by thermal insulation made of mineral fibre. The ceiling consisted of two layers of gypsum board attached to laths with insulation material between and above the laths. The thermal insulation was made of mineral fibre placed towards the ventilated cold attic room. A PE vapour barrier was placed behind the gypsum boards. On the thermographic picture to the left, the dark blue colour represents 17 °C and the yellow colour represents 24 °C. The picture to the right is an ordinary photo.

3.6 Category F: Cold areas in the thermal envelope along ceilings

Category F includes inhomogeneity in the thermal envelope at the ceiling. The areas represent thermal bridges not related to areas with a less thick layer of thermal insulation. The thermal bridges were observed as the result of cold outside air penetrating into the thermally insulated layer. The cold outside air sweeps through the wind barrier and infiltrates the thermally insulated layer as a result of gaps in the joint between wind barriers. Gaps within the thermal insulation allow the cold outside air to spread far across the ceiling.

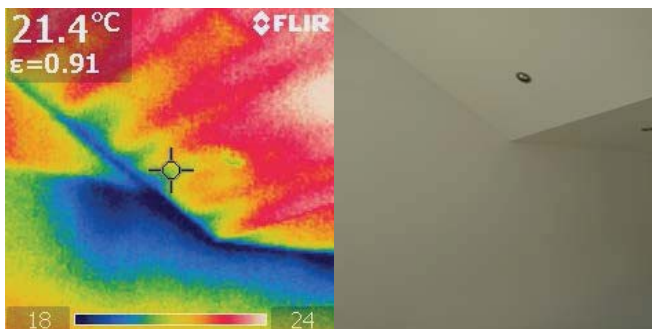


Fig. 11. Joint between the exterior wall and the ceiling in the kitchen. The kitchen-dining area was combined with the living room. The exterior walls of brickwork walls were attached to a lightweight concrete wall that served as the loadbearing inner wall separated by thermal insulation made of mineral fibre. The ceiling consisted of two layers of gypsum board attached to laths with insulation material between and above the laths. The thermal insulation was made of mineral fibre placed towards the ventilated cold attic room. A PE vapour barrier was placed behind the gypsum boards. On the thermographic picture to the left, the dark

3.7 Category G: Cold joints between building components

Category G include joints between different building components. Joints between building components were observed at door frames, window frames, at access hatches to the attic room and duct for technical supply installations going through the thermal envelope at ceilings or exterior walls.



Fig. 12. Joint between the hatches to the attic room and the ceiling of the utility room. The ceiling consisted of two layers of gypsum board attached to laths with insulation material between and above the laths. The thermal insulation was made of mineral fibre placed towards the ventilated cold attic room. A PE vapour barrier was placed behind the gypsum boards. On the thermographic picture to the left, the blue colour represents 20 °C and the red colour represents 25 °C. The picture to the right is an ordinary photo.

4. Discussion

The thermal envelope of nine first-generation low-energy buildings constructed as individual dwellings built in Denmark between 2006 and 2008 was observed by means of commercially available thermographic equipment. Measurements were made to reveal the quality of the work carried out on location when constructing a number of different types of thermal envelopes with a low heat transmission. Avoiding thermal bridges, lack of air barrier and heat loss through the strip foundation as well as other issues that increased the energy demand of the dwellings. Measures showed local areas at the thermal envelope where the overall coefficient of heat transmission increased. On a thermographic picture taken from inside the dwelling, such areas were seen as local areas with a lower temperature than seen at the overall thermal envelope, exterior walls and ceilings.

The performance of a number of different types of first-generation low-energy thermal envelopes was assessed on location. The thermal insulation used for all dwellings was based on mineral fibre and had a fixed shape. The assessment of performance was based on thermographic observations of the different dwellings once the thermal insulation was in place in the exterior walls and in attics as well as in ceilings that were parallel to the roof. Thermographic observations of the thermal envelope showed a number of local areas with an increased coefficient of heat transmission than observed for the overall high performing thermal envelope. The most important was located at joints

between building components including joints between different building components. Joints between prefabricated building components like door frames, window frames and at access hatches to the attic room and at ducts for technical supply and installations going through the high performing thermal envelope. In addition, observations also revealed spots with a lower temperature than found for the overall thermal envelope. Furthermore, it showed that for some of the exterior walls, local areas towards the ceiling were discovered to have a lower temperature than the rest of the wall, thus indicating that cold air was able to reach the inner surface. However, a minor temperature decrease was expected as the location had low temperature action from two sides, from the attic and the exterior wall, respectively. Thermal bridges that were related to the architectural design of the building and had nothing to do with the insulation material itself were also observed. The most important was located where the foundation joins the concrete slab floor and a lightweight concrete wall which served as the loadbearing inner wall. The observations and temperature measures do not come as a surprise, as these observations are commonly made in Danish dwellings (Rasmussen T. V. and Nicolajsen A. 2007, 2004, Valdbjørn Rasmussen T. et al. 2006).

Measurements revealed that when constructing high-performance thermal envelopes, special care must be taken in order to avoid cold areas in the thermal envelope, shown as a result of inhomogeneity of the thermal envelope i.e. changed thickness of the thermal insulation; cold areas in the thermal envelope along the ceiling and; cold joints between building components, illustrated as Categories E, F and G, respectively.

5. Conclusion

The thermal envelope of nine first-generation low-energy buildings constructed as individual dwellings built in Denmark between 2006 and 2008 was investigated. The dwellings were constructed with focus on low heat transmission of the thermal envelope. During winter the thermal envelope was observed by means of commercially available thermographic equipment. The investigation covered a real-life situation where the inhabitants and normal weather conditions influenced the thermal envelope. The measurements showed the need for improvements when constructing low-energy buildings that meet requirements of high-performance thermal envelopes. Thermographic observations were made at the internal surface of the thermal envelope. Observations show the appearance of local areas with a lower temperature than for the overall thermal envelope regardless of the type of construction observed. The lower temperature appears as well-defined areas at the internal surface of the thermal envelope. However, the measured temperature difference between the area with a lower temperature and the temperature at the overall surface is in general minor. Even though there are deviations between the measured temperature differences, no significant pattern was found when observing a thermal envelope constructed either as a wood-stud construction or a lightweight concrete construction.

The reason for the areas of a lower temperature at a local area must be further investigated to be certain of the building physics causing the temperature drop. Further investigations can be done by opening the construction. However, a good

impression was found by combining temperature measures with the construction principles used for the individual dwellings.

The observations and temperature measures do not come as a surprise, as these observations are commonly made in dwellings as a result of the traditional ways of constructing buildings in Denmark. Nevertheless these findings were unexpected in dwellings constructed with the priority to construct high-performance thermal envelopes. Measurements showed that the use of thermal insulation materials did not take advantage of their full potential. Lack of wind barriers allowed insulation materials to be ventilated with cold air from the outside. In most cases local changes in heat transmission of the thermal envelope were observed where finished building components were mounted i.e. around window frames and door frames as well as around hatches to the attic room, thus leaving room for developing suitable design solutions. Furthermore, suitable design solutions are needed where party walls are attached to the thermal envelope and for corners pointing in as well out of the thermal envelope, as well as the joint between the thermal envelope, the secular foundation and the concrete slab floor.

Observations revealed the need for quality assurance of the thermal envelope to ensure that high-performance thermal envelopes are constructed to perform with a coefficient of heat transmission as expected and provided in the design state.

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